Ecological Engineering 37 (2011) 850–863

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Stormwater ponds and biofilters for large urban sites: Modeled arrangements that achieve the phosphorus reduction target for Boston's Charles River, USA

Stephanie E. Hurley*, Richard T.T. Forman

Harvard University, Graduate School of Design, Cambridge, MA 02138, USA

ARTICLE INFO

Article history:
Received 2 June 2010
Received in revised form 12 January 2011
Accepted 22 January 2011
Available online 22 February 2011

Keywords:
Urban stormwater
Total Maximum Daily Load (TMDL)
Detention pond
Biofiltration
Bioretention
Phosphorus
Water quality
Low Impact Development (LID)

ABSTRACT

Urban rivers daily receive tons of phosphorus and other pollutants from stormwater generated by impervious surfaces. Constructed detention ponds and biofiltration cells (biofilters) are often effective for localized stormwater treatment, yet less is known about their effectiveness for large built areas. Our goals were to assess stormwater phosphorus-removal relative to total percent cover, number, size, and configuration of detention ponds and biofilters. Two approximately 200-ac. (80 ha) industrial and institutional sites near Boston's Charles River containing diverse smaller drainages, land uses, and runoff sources were analyzed. Using the model WinSLAMM, P-reduction percents were calculated and compared for detention ponds (1–40 per site; covering 5–15% of their drainage areas) and biofilters (two sizes, with and without underdrains; ∼900–4300 per site; 5–10% cover). The government's proposed TMDL target of 65% P-reduction was only achieved with designs that treated 100% of urban land with a pond or biofilter. The 65% target was met by a single pond covering 5% of the site and by several multi-pond or biofilter arrangements with coverage ranging from 5% to 10%. A stringent water quality goal of 75% P-reduction was also attained with certain consolidated and dispersed pond and biofilter designs. Configuration of treatment landscapes appeared to be more important than total treatment area. Results were generally similar for the large institutional and industrial sites. Stormwater P-reduction goals can be creatively met with diverse, realistic land allocations for ponds and biofilters, which also provide enhanced aesthetics, recreation opportunities, and other benefits beyond water quality.

1. Introduction

Urban rivers receive flows from built watersheds, replete with impervious surfaces that yield polluted stormwater runoff. Indeed, conventional urbanization and development practices typically alter hydrology and impair water quality throughout stream and river systems, as well as their receiving waters (e.g., Azous and Horner, 2001; Dietz, 2007; Forman et al., 2003; Marsalek et al., 2008; Schueler et al., 2009). Among the array of pollutants, the nutrient phosphorus (P) is of major concern for degrading water quality in freshwater ecosystems.

In Boston's Charles River, as in countless other urban watersheds, P is considered to be the limiting nutrient triggering blue-green algae (cyanobacteria) blooms, and leading to eutrophication of the river system. Stormwater runoff contributes significantly to P-loading in the Charles River (Massachusetts, 2007). In 2007, Federal and State environmental regulators approved a Total Maximum Daily Load (TMDL) for the Charles River. The TMDL document states that the River's health can only be restored through reductions in P-loading from urban land uses and requires a 65% reduction in P-loading from industrial, commercial, institutional, and high-density residential land-uses in the watershed (Massachusetts, 2007).

Presently, the U.S. Environmental Protection Agency (EPA) and Massachusetts Department of Environmental Protection are considering regulations to legally require 65% reductions of P in stormwater runoff from urban land uses, and are embarking on a process of selecting which properties to regulate first (EPA, 2008; Massachusetts, 2007). EPA has proposed that as a pilot study for three towns in the Charles River Watershed all properties with more than two acres (0.81 ha) of impervious surfaces must be retrofitted to meet the 65% P-reduction level.

With increasing interest in the last two decades, retrofits using Best Management Practices (BMPs) and Low Impact Development (LID) planning strategies have been developed in an effort to combat phosphorus pollution and other water quality and hydrology problems associated with urban runoff (e.g., Coffman, 2002; Field

* Corresponding author. Present address: University of Vermont, Rubenstein School of Environment and Natural Resources, 81 Carrigan Drive, Burlington, VT 05405, USA. Tel.: +1 802 917 3052.
E-mail addresses: stephanie.hurley@gmail.com, shurley1@uvm.edu (S.E. Hurley).

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doi:10.1016/j.ecoleng.2011.01.008

et al., 2005). Numerous studies have indicated the success of BMPs and LID, which use vegetation and soils to intercept, slow, filter, and infiltrate stormwater runoff, for improving water quality and hydrology on a localized site scale (Barrett, 2005; Center for Watershed Protection, 2007; Hogan and Walbridge, 2007; Larm, 2000; Mallin et al., 2002; Weiss et al., 2007). Less is known about the potential to improve downstream water quality by employing stormwater treatment landscapes across large portions of urban watersheds. There is a need to go beyond the site scale to the watershed scale (e.g. Field and Sullivan, 2003; Jing et al., 2006; Rowney et al., 1997; Tilley and Brown, 1998).

Using two relatively large ~80 ha (~200 acre) sites in the lower Charles River watershed, this modeling study examines potential water quality improvements associated with stormwater treatment landscapes (detention ponds and biofiltration cells) on a watershed planning scale. Both study sites contain mostly post-industrial land uses and are slated for redevelopment. This provides a rare opportunity to reconsider stormwater drainage infrastructure on a broad scale, within an area that has long been urbanized. We evaluate a spectrum of different sizes and distributions of stormwater treatment landscapes across both sites, one mainly industrial, and the other with predominantly institutional land uses.

While it is clear that throughout urban areas, and especially near roadways, more vegetated stormwater treatment landscapes are needed to mitigate the effects of stormwater (Forman, 2008), we identified a need for research into the patterns or organization of these stormwater treatment landscapes at the urban neighborhood (or sub-watershed) scale. Conventional "end-of-pipe" stormwater management has typically used drainage pipes to convey stormwater to one or a few large parcels for treatment, i.e., a "consolidated" arrangement. More recent stormwater management strategies, by contrast, employ a "start at the source" concept (BASMAA, 1997), aiming to treat stormwater runoff as close as possible to where it lands as rainfall, i.e., a "dispersed" arrangement. The spectrum of distributions of stormwater treatment landscapes we model ranges from "consolidated" to "dispersed" to "highly dispersed."

This study focuses on the arrangement of two commonly designed and implemented stormwater treatment landscape types: wet detention ponds and biofiltration cells. "Wet detention ponds" (henceforth referred to as "ponds") are engineered to retain some standing water at most times; the primary P-removal (herein used synonymously with P-reduction) mechanism in these ponds is sedimentation, which is correlated with retention time of the runoff within the pond system (Braskerud et al., 2005; Mallin et al., 2002; Weiss et al., 2007). "Biofiltration cells" (biofilters) rely upon soil filtration processes as the primary mechanism for P-removal, with additional removal due to uptake by vegetation (Davis et al., 1998; Dietz, 2007; Hsieh and Davis, 2005).

Total phosphorus (TP) comprises dissolved and particulate forms of P. We chose total phosphorus, rather than using dissolved, bioavailable phosphorus as the assay for this study largely because total phosphorus is the measurement used in the government's Charles River TMDL analyses and anticipated regulations. Also, Hakanson et al. (2007) strongly recommend the use of TP instead of bioavailable P as a basis for predicting chlorophyll-a and cyanobacteria when modeling at the ecosystem scale.

The TP removal performance of both ponds and biofilters is known to be quite variable, depending on design, location, and other conditions. Note that in some cases negative TP-removal rates, net exports of TP, are reported. A database created by the Center for Watershed Protection (2007) reports that detention ponds typically remove 52% of TP (range 12 to 91%), while biofiltration removes 5% TP (range −100% to 65%). Weiss et al. (2007) report 52% (±23%) removal by detention ponds and 72% (±11%) by biofiltration. The University of New Hampshire Stormwater Center (2009) reports ranges of P-removal from 30% to 90% by retention ponds and from 35% to 80% by bioretention systems. Other studies of the TP-removal by detention ponds report 60–70% TP-removal (Pitt and Voorhees, 2003a) and 35–60% TP-removal (Welch and Jacoby, 2004). Dietz (2007) describes a wide range of biofiltration cell performances from −240% to 87% TP-removal. Davis et al. (1998) report high TP-removals by biofiltration of 70–83%. In addition to evaluating removal from existing pond and biofiltration systems, many authors also recommend ways in which the design, construction, and maintenance of these systems could be improved for greater capture of TP (e.g., Davis et al., 1998; Dietz, 2007; Pitt and Voorhees, 2003a).

Many of the above authors' suggestions for maximizing P-removal were incorporated in our pond-and-biofilter modeling. Design recommendations refer to sizing of the treatment systems and outlets, steepness of side-slopes in ponds and biofilters, biofilter infiltration media selection and presence or absence of an underdrain, and the inclusion of a vegetated bench/shelf in ponds (see Section 2.3). For construction, these include assumptions that the subsoils at pond and biofilter bottoms are not compacted and that proper erosion and sediment control practices are used. A "gardening" approach is recommended for maintenance of biofilters, as well as the vegetated areas surrounding ponds; this approach incorporates regular inspections, removal of leaf litter in the fall and of clippings post-mowing or pruning, and re-vegetating bare areas to minimize side-slope erosion. Possible explanations for the negative removals reported above—i.e., exports of P from pond and biofilter systems—which can be addressed through proper design, construction, and maintenance, include excessive soil disturbance during construction, lining systems with materials that minimize infiltration and decrease contact time between runoff and soils, applying mulch that leaches P, and allowing vegetation to decay in place (Dietz, 2007; Dietz and Clausen, 2005; Reinelt and Horner, 1995).

The goals of this research are to evaluate the effects on water quality, i.e., level of phosphorus reduction from stormwater, associated with:

(A) Percent cover of site by detention ponds or biofilters; and
(B) Distributions (numbers/sizes/locations) of ponds and biofilters within a site.

2. Methods

2.1. Study sites

The two study sites are the Allston Campus Institutional Site and Zakim Industrial Area (abbreviated herein as the "Institutional Site" and "Industrial Site") (Fig. 1). The institutional site is a 75-ha (185 acre) Harvard University campus expansion in the Allston neighborhood of Boston, MA. Although it is predominantly institutional, the site also contains mixed use, residential, commercial and some industrial activities. The industrial Zakim site is an 80-ha (200 acre) area located in Somerville, MA within the former Millers River drainage (a river now almost entirely filled in). Runoff from the industrial site flows, via the remaining fragment of the Millers River, to the Charles River just north of downtown Boston. The industrial site is being redeveloped to include more mixed-use residential and commercial land uses.

Both sites have been used for numerous industrial and commercial activities in the past centuries. Both study sites are nearly flat and located on almost entirely "fill" soils, which include contaminated soils (brownfields). Both sites contain "buried streams"

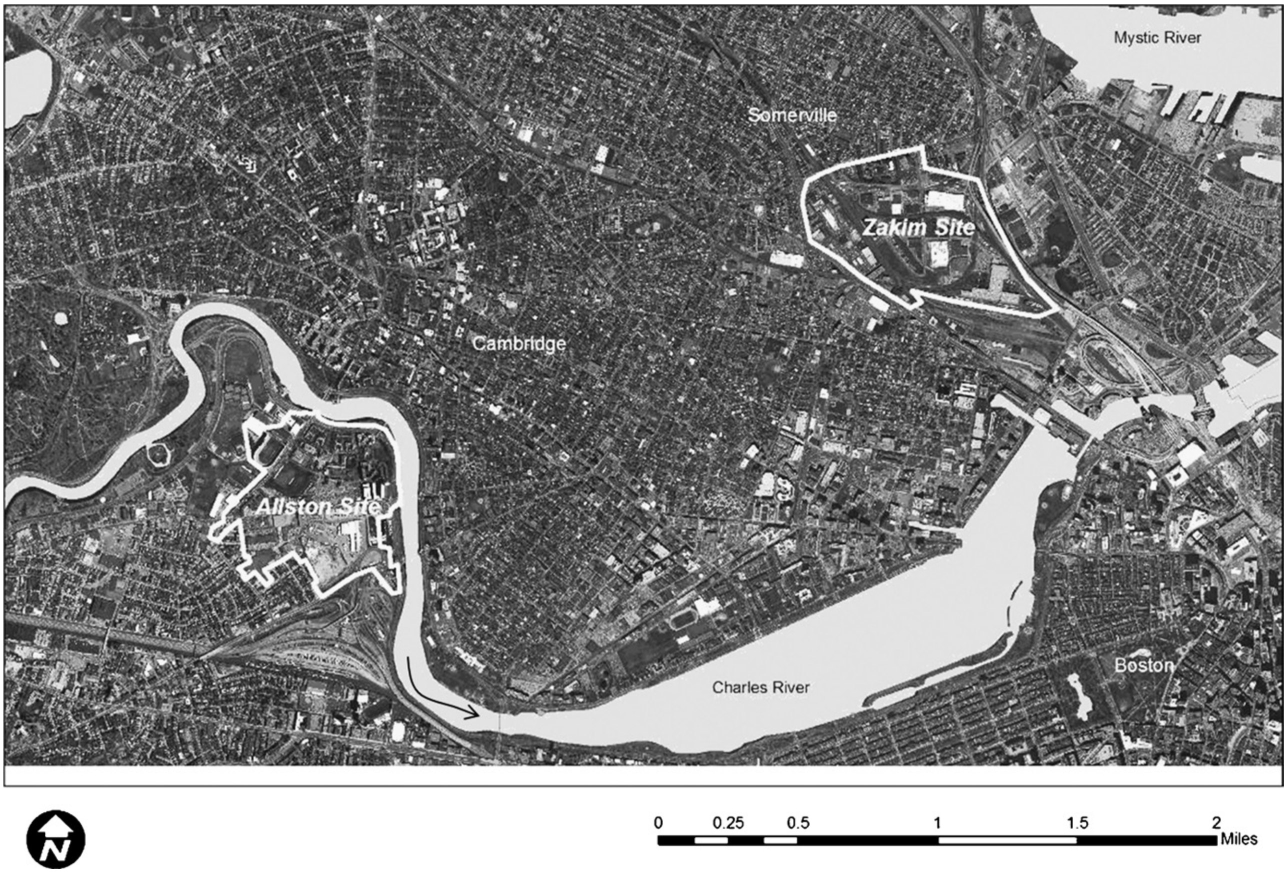

Fig. 1. Allston Institutional and Zakim Industrial study sites.

within pipes beneath areas that are now largely paved. Similar "ultra-urban" sites can be found in many urban watersheds around the world; however, the methodology presented here is particularly useful for developed countries with temperate climates.

The predominant existing land uses of the institutional site (Fig. 2) are "Institutional" and "Mixed Use." A small "General Business" commercial area and a small Multi-Unit High Density Residential area are present. Five Drainage areas are present: A = 12.9 ha (~32 acre), B = 24.3 ha (~60 acre), C = 11.7 ha (~29 acre), D = 7.3 ha (~18 acre) and E = 18.6 ha (~46 acre). Only Drainages C and E are completely located within a single land use; the other drainages include more than one land use. Stars indicate stormwater outfall locations for the five drainages. The Mixed Use area has historically been used for industrial, commercial, residential, and transportation-related activities. In the future, most of this site is scheduled for institutional uses.

The industrial site's (Fig. 3) predominant existing land use is "Light Industrial," with two sections separated by rail tracks (Drainage X = 34 ha (~84 acre); Drainage Y = 14.2 ha (~35 acre). A "General Industrial" land use, with private stormwater drainage pipes, that is operated by the railway (Drainage Z = 24.7 ha (~61 acre) and a small "General Business" commercial area (Drainage W = 8.1 ha (~20 acre) are also present. The stormwater from all of these land use-drainages eventually outfalls to the Millers River and the Charles River, southeast of the site, represented by the star symbol. The Light Industrial areas of this site have historically hosted industrial, commercial, and transportation-related activities, with a few residential units. In the future, many parts of these drainage areas are scheduled to be redeveloped for mixed use residential and commercial activities.

Although the land uses in the institutional and industrial sites are different (Figs. 2 and 3), the study sites are relatively similar in their composition of different sources for stormwater runoff (Fig. 4). Both sites have extensive areas of paved parking lot, roofs, and streets. The institutional site has considerable large landscaped area, whereas the industrial site has much unpaved parking and train track area.

2.2. Modeling and SLAMM

Both regression equations (stochastic) and process-based (deterministic) water quality models can satisfactorily estimate pollutant loads from impervious surfaces associated with individual rain events (Vaze and Chiew, 2003). We chose process-based modeling, with a "continuous simulation" approach, to characterize long-term performance and to compare a wide spatial array of ponds and biofilters for urban conditions. Widely used examples of continuous simulation models include Storm Water Management Model (SWMM), Storage Treatment Overflow Runoff Model (STORM), Hydrological Simulation Program-Fortran (HSPF), and SLAMM (Chow and Yusop, 2008).

We selected WinSLAMM (the Source Loading and Management Model for Windows, or simply SLAMM) (©Pitt and Voorhees, Version 9.3, 2008) for evaluating the potential reductions of phosphorus loading to the Charles River that could be associated with different sizes, numbers, and configurations of stormwater ponds and biofiltration cells (biofilters) within two large urban redevelopment sites. The attributes of SLAMM that influenced our selection of this model include:

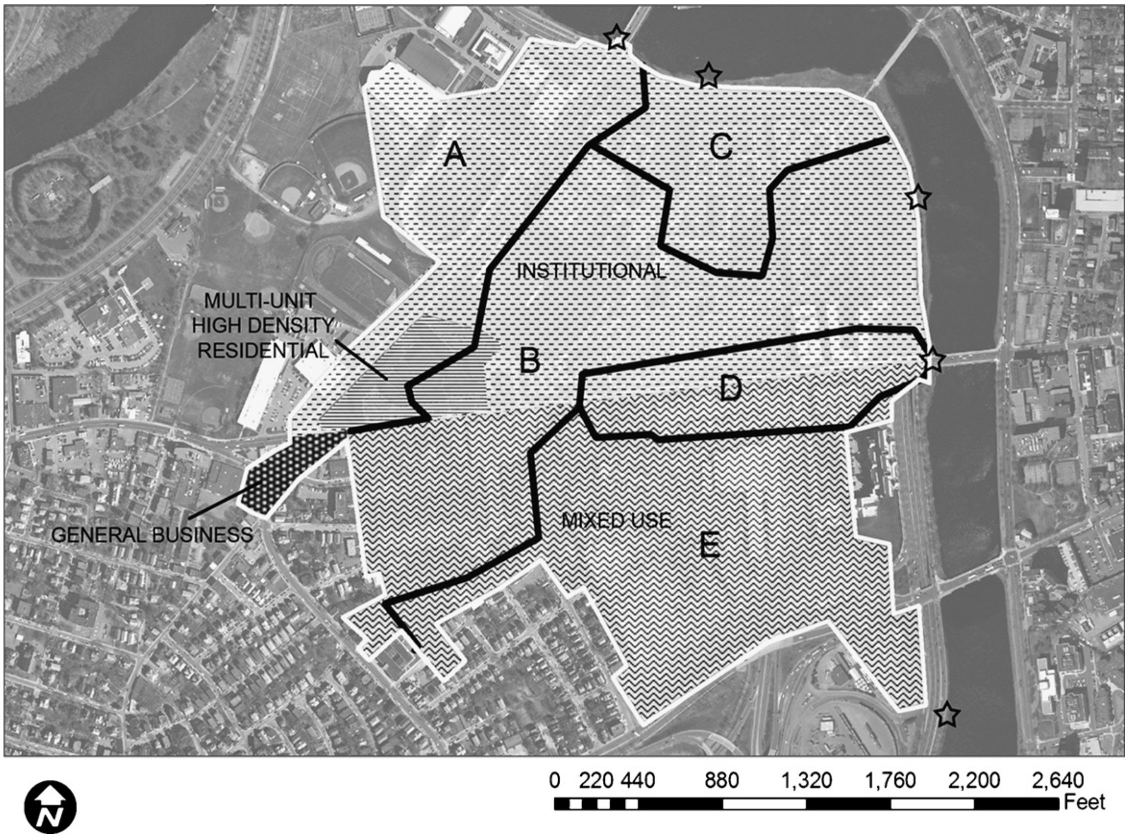

Fig. 2. The 75-ha (185 acre) Institutional Site in Allston, Boston, MA. The white line indicates the site boundary. Five Drainages (labeled A–E) are delineated by black lines. 'Star' symbols indicate locations of stormwater outfalls from each drainage to the Charles River. Four land uses are indicated by different shading and are labeled.

- Continuous simulation of pollutant loading from impervious areas and 'stormwater treatment landscape' performance over decades of rainfall.
- Emphasizes water quality explicitly, rather than looking at water quality as merely an aspect of hydrology/hydraulics.
- Designed for modeling sites in urban and suburban environments.
- Phosphorus output results in three forms: dissolved, particulate, and TP.
- Phosphorus reported as both concentrations (output as mg/L) and yield or loading (output as pounds (lbs.); 1 lb. = 454 g).
- Ability to model multiple ponds and biofiltration cells of different sizes and in different locations within the watershed.
- User-friendly interface, suitable for use by planners and regulators (Pitt and Voorhees, 2003).

Founded on data from the original National Urban Runoff Program (NURP) Study (EPA, 1983), SLAMM has been frequently updated and calibrated using field data from across the U.S., including performance data from commonly employed stormwater treatment BMPs (e.g., Bannerman et al., 2003; Corsi et al., 1997; Graczyk et al., 2003; Pitt et al., 2005a,b; Selbig and Bannerman, 2008). SLAMM has been utilized extensively by the Wisconsin Department of Natural Resources and the United States Geological Survey for urban watershed modeling (USGS, 2009; WiDNR, 2010).

In this Charles River basin study, SLAMM was used to model predicted phosphorus loading—measured as Total Phosphorus (TP)—based on existing conditions, and to compare those values with the modeled P-loading likely to occur when ponds or biofilters were inserted into the same sites.

A hierarchy of runoff-producing areas is recognized for "watershed scale" sites. Each hierarchical level influences the hydrology and water quality of stormwater runoff and is useful in sizing treatment landscapes such as ponds or biofilters. The largest area (broadest category) is the "Site," ~75 ha (185 acre) for the institutional site and ~80 ha (200 acre) for the industrial site. Site boundaries may be defined by physical, hydrological, or political criteria.

Next is the "Drainage," or "sub-watershed," which describes a hydrologically connected area of land, from which stormwater is conveyed to a single outfall. The conveyance of stormwater through a drainage may be the result of natural topography and surface flows, or controlled by a constructed stormwater pipe system. Both study sites include several distinct drainages, which differ in their hydrology and the type of pipe system present.

The next runoff-producing area is termed "Land Use." Land uses such as industrial, commercial and residential are determined by the zoning of an area and the current activities thereon, which influence the amount and character of pollutants in stormwater runoff. Land uses are generally not based on drainage system features, so for example, two different drainages may be present within a single large land use (e.g. X and Y in Light Industrial; Fig. 3), or a single drainage may contain more than one land use (e.g. D containing Institutional and Mixed-Use; Fig. 2).

The smallest areas, "Sources," are surface types within a land use that produce runoff. These include roof tops, parking lots, streets, landscape areas, sidewalks, compacted soil, and so forth. Each source has a distinct texture, which affects its contribution to the interception, transport, pollutant accumulation, flow rate, and volume of stormwater runoff. In SLAMM modeling, sources are nested within land uses and each source has distinct attributes,

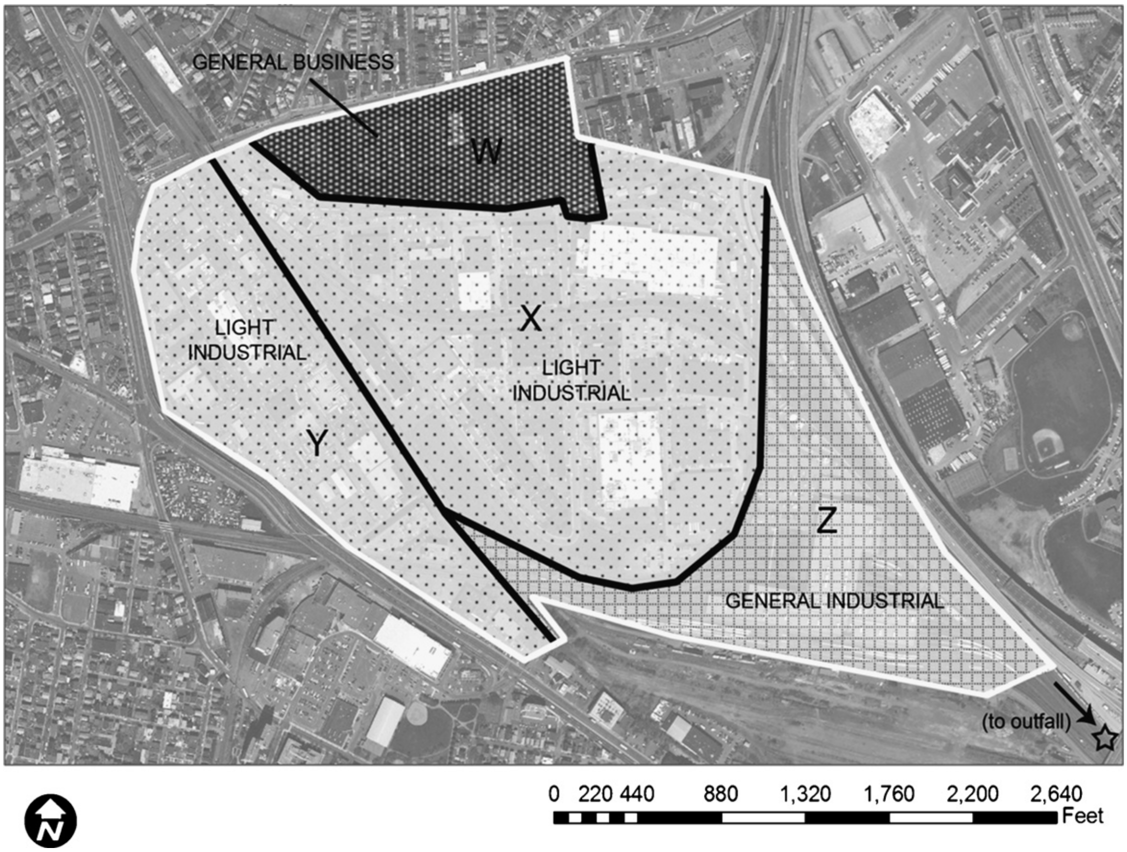

Fig. 3. The 80-ha (200 acre) Industrial Site in Zakim, Somerville, MA. The white line indicates the site boundary. Four Drainages (labeled W–Z) in this site, correspond with three land uses and are separated by black lines. This stormwater pipes on this site outfall to the Charles River via the ~1/4 mile (~400 m) Millers River (southeast and just off the map).

such as the soil type of a landscaped area, the width or surface condition of a road, or whether a roof is flat or sloped.

The following steps outline the way that pollutant accumulation and transport in runoff are calculated in the SLAMM model (Voorhees, personal communications, 2008):

1. Calculate runoff generated from sources.
2. Sum the source runoff for each land use.
3. Route runoff from the land uses through a drainage.
4. Route runoff from the drainage to the outfall discharging to receiving waters.

The above sequence applies whether one is modeling existing (baseline) conditions, with no stormwater treatment landscapes, or proposed future conditions in which ponds and biofilters are added for pollutant removal.

SLAMM enables the modeler to make detention ponds the recipient of all runoff from a site, or from a drainage within it, by locating a pond at the stormwater pipe outfall. Alternatively, ponds can receive runoff from individual source (e.g., a pond can be modeled to receive runoff from a specific parking lot), though not from a particular land use. Biofilter modeling in SLAMM has one additional option: SLAMM enables the modeler to locate biofilters at site outfalls or with specific sources, as well as with a particular land use. For example, using SLAMM, one or more biofilters can be distributed across an industrial or commercial land use. In this case, the biofilters are not affiliated with individual sources, but treat runoff from all sources within a given land use.

2.3. Ponds and biofilters

We use the term “pond” to describe wet detention ponds and/or basins, which generally have some water in them during the majority of the year. The ponds modeled using SLAMM in this study typically hold a minimum of 0.91 m (3 ft) of standing water within their deepest areas (Fig. 5). These are not dry detention ponds designed to dry out between rain events, nor retention ponds designed for stormwater storage and infiltration into soils and groundwater. In both study sites urban fill soils and contamination limit opportunities for infiltration.

All ponds have rarely flooded shallow side slopes (5%) at the upper water level; steep side slopes (25%) down to ~0.91 m (~3 ft) water level; a relatively flat shelf (2% slope) at ~0.91 m (3 ft); and steep slopes (25%) to the pond floor (Fig. 5). These slopes enhance runoff volume capacity for the pond, while creating a flat shelf that allows aquatic vegetation growth plus, for safety, a shallower shelf surrounding the pond. Between rain events, the typical standing water height will be 0.91–1.22 m (3–4 ft) above the pond. All ponds include two outlet structures: one V-notch weir with a 60° opening at 1.37 m (4.5 ft) water surface elevation, and one 3.05 m (10 ft)-wide broad-crested weir at 1.5 m (5 ft) water surface elevation.

We use the term biofiltration to describe the treatment of stormwater utilizing vegetated depressions underlain by a mix of engineered soils designed to maximize localized storage volume and rates of absorption and filtering of stormwater. Relative to similar terms like “bioretention system” and “raingarden” (which essentially describe the same types of stormwater treatment landscapes), we chose the term “biofiltration” as it seems most expressive of the soil and vegetation based phosphorus removal

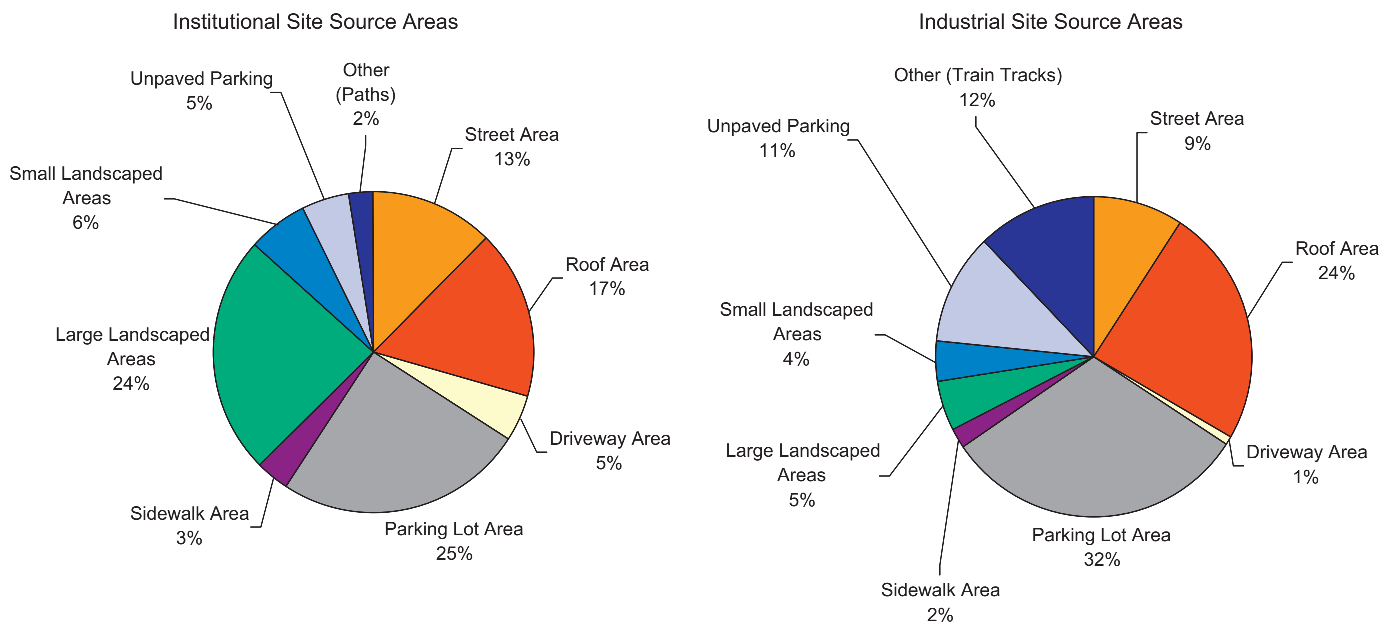

Fig. 4. Percent total area for each type of "source area" contributing stormwater runoff within a study site. The Institutional Site (Allston) is 185 acres (75 ha); the Industrial Site (Zakim) is 200 acres (80 ha).

processes modeled herein. In addition, SLAMM evaluates performance of biofiltration systems using its "biofilter" function so we adopted the term biofilter as well. Due to the type of soil and fill, risk of brownfield contamination, and the relatively shallow depth to the groundwater table at the study sites, the biofilters modeled are designed to minimize infiltration into surrounding soils. Their design emphasizes short-term water storage and pollutant removal within the biofiltration cells themselves.

Two sizes of biofilters were modeled: large (~37 m^2; 435 ft^2) and small (~18.5 m^2; 200 ft^2). All biofilters, have a shallow side-slope at the top for safety with vertical sides below (Fig. 6). A ~0.3 m (1 ft)-wide overflow weir outlet directs runoff back into the storm drainage system. Biofilters with an underdrain (Fig. 6) and without an underdrain were used in modeling. We chose the presence of an underdrain as a major variable because the use of underdrains continues to be debated by designers of biofiltration and bioretention systems (Davis et al., 2009) (see Section 4).

Slightly different variables affect the phosphorus removal performances of ponds and biofilters, though the area to be drained and storage/size of the treatment system are the most significant for both ponds and biofilters. Detention pond function also depends on the outlet size/type and edge vegetation. Somewhat differently, biofiltration also depends on the presence/absence/size of an underdrain, infiltration rate of varied substrates and surface outlet size/type.

Taking into account all variables and their estimated relative effects on phosphorus removal from urban stormwater using the WinSLAMM model (1 = most influential; 5 = least influential), wet detention pond performance depends on the (1) water volume to be treated (proportional to drainage area from which runoff is captured); (2) pond size (volume = area × depth); (3) outlet size(s) and shape(s) (discharge rate); and (4) pond edge vegetation (estimated in the model as a function of area of pond edge and side slope at different water levels). For biofilters, variables affecting performance (again, 1 = most influential; 5 = least influential) include (1) water flow to be treated (proportional to drainage area from which runoff is captured); (2) stormwater storage (volume = area × depth), (2) the presence or absence of an underdrain; (3) infiltration rate of engineered soil, (3) infiltration rate of rock fill; (4) infiltration rate of native soil, (4) engineered soil type (e.g., peat, sand, and com-

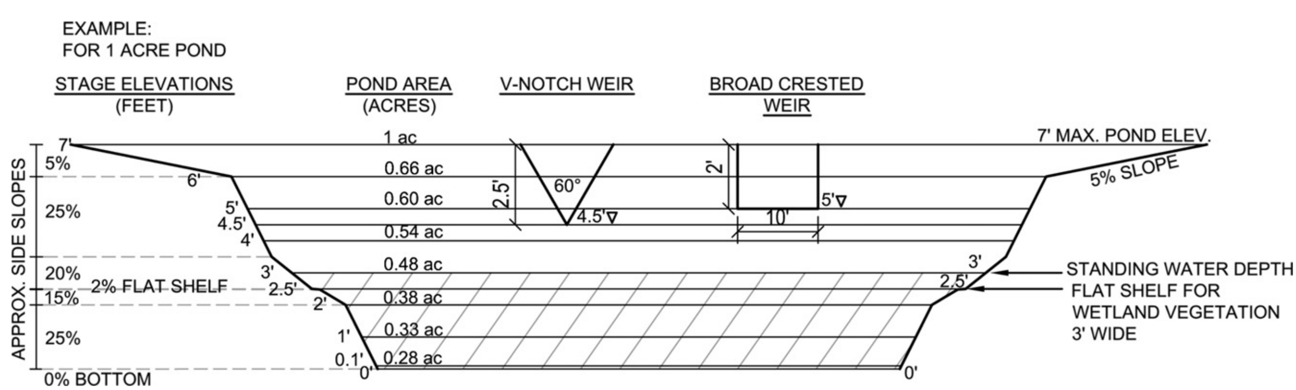

Fig. 5. Section of typical wet detention pond modeled in SLAMM. The pond dimensions listed are based on a surface area of 1 acre; surface areas (land cover) of all ponds modeled in this study varied according to the scenario applied. However, all ponds were proportional to the pond depicted here. Notes on the scale: vertical scale exaggerated for visualization, 1′ (1 ft) = ~30.4 cm; 1 acre = ~0.40 ha. Units are written in the U.S. customary system as these units of measure are used for both SLAMM modeling and for meeting local regulatory requirements.

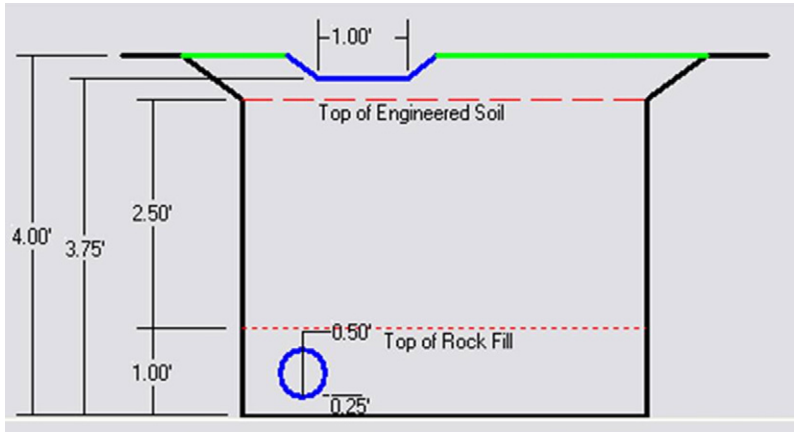

Fig. 6. Section of a typical biofilter modeled in SLAMM. Circle near the bottom indicates an "underdrain" pipe (a perforated pipe that connects to the storm sewer system), which is included in certain model runs. 1′ (1 ft) = ~30.4 cm. Units are written in the U.S. customary system as these units of measure are used for both SLAMM modeling and for meeting local regulatory requirements.

post), (4) underdrain orifice size (diameter) or discharge rate (if underdrain is present); and (5) size and shape of overflow outlet at top (discharge rate).

2.4. Size, number, and distribution of stormwater treatment landscapes: consolidated or dispersed?

Pre-trial modeling indicated that in treating stormwater to achieve P-loading reductions of about 65%, ponds or biofilters should cover approximately 10% of the drainage area from which they receive runoff. Thus, in the 140 different model runs in this study we used percentages of drainage area for treatment from 5% to 15%.

Configurations (distributions within the landscape) of the modeled ponds and biofilters spanned a spectrum from "consolidated" to "dispersed" to "highly dispersed" within the study sites. For example, a single pond designed to *consolidate* and collect runoff from an entire 80-ha (~200-ac) site—sized at 10% of the site's drainage area—occupied 8 ha (~20 acre). Forty ponds *dispersed* throughout the site—with each pond sized proportionally at 10% of the source area draining to it—collectively also occupied 8 ha, or 10%, of the 80-ha study site. At the *highly dispersed* end of the spectrum, 2000 biofilters—each sized at 40.4 m^2 (435 ft^2, or 1/100th of an acre)—covered 8 ha, or 10% of the site.

2.5. Scenarios

To provide a spectrum of pond and biofilter distributions for each of the two study sites, we developed a set of hypothetical policy scenarios that could be used by a regulatory body to plan for urban stormwater treatment. These scenarios include six detention pond scenarios (Table 1) and four biofilter scenarios (Table 2), which yielded a total of 116 detention pond model trials and 24 biofiltration model trials. The policy scenarios are in part based upon real scenarios for stormwater management now being considered for three towns in the upper Charles River watershed in Massachusetts, wherein landowners would be regulated based on acreage (1 acre = 0.4 ha) of impervious area on their property (see Section 4).

SLAMM and Microsoft Excel programs were used to calculate expected phosphorus loadings from all rains during the years 2000–2006. The removal of phosphorus associated with each scenario was calculated for this seven-year period by comparing the modeled baseline conditions (i.e., no ponds or biofilters present) with the TP export results when the given scenario (i.e., with stormwater treatments present) was applied for the same time period. Phosphorus removal is then expressed as a percentage (Eq. (1)).

$$\text{Percent of P-removal} = \left[1 - \left(\frac{\text{TP in runoff with stormwater treatments present}}{\text{TP in runoff with no stormwater treatment}}\right)\right] \times 100 \qquad (1)$$

For the One Pond Scenario, we created a single SLAMM file for each study site, i.e., one for the institutional site (Allston) and one for the industrial site (Zakim) (Table 1) and compared ponds sized at 5%, 7.5%, and 10% of each site's total area. Due to size limitations in the modeling program, a single SLAMM file was not possible for the five multi-pond scenarios, so we modeled these (Scenarios 1–5) using separate SLAMM files, one for each drainage area within a site. Weighted averages of P-removal for all ponds across all drainages were calculated and reported in order to address the disparity in areas (sizes) of the drainages. P-removals from larger drainages in a site are 'weighted' proportionally higher than P-removals from the smaller drainages when averaging the removals across a whole site.

Biofilter scenarios were modeled to evaluate distributions of numerous biofilters collectively occupying 5%, 7.5% or 10% of the two sites' land areas (Table 2). Each modeling scenario was evaluated for biofilters with underdrains and biofilters without underdrains. All biofilters include an overflow outlet at the designed maximum water surface elevation. Those "with underdrains" include a second outlet: a subsurface perforated pipe that discharges treated water from the bottom of the biofilter soil layers into the storm drainage system. When no underdrain is present, the primary outlet for runoff (at the top of the biofilter) is activated when the biofilter is filled. In SLAMM modeling, numerous biofilters can be distributed across each land use within a site. We created one SLAMM file for each study site and changed the biofilter sizes and numbers (according to the percent coverage being modeled: 5%, 7.5% and 10%) within each land use for each model trial.

2.6. Other data

We used precipitation data for the years 2000–2006 from Boston's Logan Airport, approximately 3 miles east of the industrial site and 5 miles east of the institutional site. SLAMM allows con-

Table 1
Detention pond scenarios modeled for each study site. All pond scenarios were evaluated for ponds modeled to occupy 10% and 15% of the runoff-producing areas. Runoff to ponds may be produced by sites, drainages, or sources; a site is composed of drainages, which are covered with sources (see Methods). 1 acre = 0.4 ha. Total pond surface area refers to the size of an individual drainage area in a site times the percent (from 5% to 15%) of the drainage to be occupied by ponds. Only the first two scenarios listed were evaluated for ponds also sized at 5% and 7.5% of their drainage areas.

Scenario name	Scenario description (runoff-producing area in *italics*)	Institutional site (Allston) ~ 75 ha			Industrial site (Zakim) ~80 ha		
		Number of ponds in site	Percent of treated area in ponds	Total pond surface area (ha)	Number of ponds in site	Percent of treated area in ponds	Total pond surface area (ha)
One pond	Entire *site* has one pond	1	5	3.74	1	5	4.05
			7.5	5.62		7.5	6.07
			10	7.49		10	8.1
			15	11.23		15	12.15
Scenario 1	Each *drainage* has one pond	5	5	3.68	4	5	4.01
			7.5	5.58		7.5	6.03
			10	7.45		10	8.05
			15	11.17		15	12.15
Scenario 2	Each *source* ≥4 acres (1.62 ha) has one pond	9	10	2.7	14	10	6.1
			15	3.8		15	8.9
Scenario 3	Each *source* ≥2 acres (0.81 ha) has one pond	25	10	4.7	19	10	6.6
			15	6.1		15	9.8
Scenario 4	Each *source* ≥1 acre (~0.4 ha) has one pond	35	10	5.3	25	10	6.9
			15	6.8		15	10.3
Scenario 5	Each *source* ≥1 acre (0.4 ha) has one pond AND one pond is added to each drainage to accept runoff from *sources* <1 acre (0.4 ha)	40	10	7.5	29	10	8.1
			15	9.2		15	12.0

tinuous simulation of all rain events, rather than analyzing runoff behavior for individual storm events. Accordingly, the calculated runoff volumes are influenced by antecedent wet and dry periods, as well as a site's soil types and the imperviousness of the land uses and source areas being modeled.

We considered scenarios for wet detention ponds or biofiltration to be "successful" (in terms of improved water quality) if they were shown via SLAMM modeling to reduce phosphorus loading to the Charles River by 65% or more compared with baseline modeling results. We also looked for scenarios reaching the 75% P-removal level as an enhanced safety margin target for cleaner water. The 65% measure of success was adopted directly from the Phosphorus TMDL for the Charles River determined by Federal and State agencies (Massachusetts, 2007).

3. Results

3.1. Baseline modeling of existing conditions

Baseline modeling was done to assess expected phosphorus loading from each study site as it exists today, without ponds or biofilters (or any other significant form of stormwater treatment). At present, both the 75-ha (185 acre) institutional site and the 80-ha (200 acre) industrial site are annually sending >275 kg (~610 lbs.) of phosphorus into the river (Table 3). Phosphorus is considered to be the prime eutrophication-causing pollutant in the slowly flowing Lower Charles River. Despite striking differences in drainage areas, land uses, and sources (Figs. 2–4) the annual P-loading for the two sites was calculated to be nearly the same (277 kg/yr versus 278 kg/yr). At the institutional site, P-loading per hectare ranged from 2.3 to 4.8 kg/yr, with the highest per-hectare P runoff in the largest drainage (B). At the industrial site, annual P-loading per hectare ranged from 2.0 to 6.1 kg/yr, with the highest rate in the second-largest drainage (Z).

3.2. One Pond Scenario, with 5–15% total pond surface area

We next compared the baseline results to the results for model trials for detention ponds based on policy scenarios (Table 1) that could be implemented to reduce P-loading to the Charles River.

The One Pond Scenario met the 65% P-removal target using all four modeled pond surface areas for both the institutional and

Table 2
Biofilter scenarios modeled for each study site. Numerous identical biofilters were incorporated in SLAMM for each modeling trial, based on the percent of site and number of biofilters indicated in the table. Each modeling trial scenario was evaluated twice: once for biofilters with underdrains and once for biofilters without underdrains. 1 acre = 0.4 ha.

Scenario name	Institutional Site (Allston) ~75 ha			Industrial Site (Zakim) ~80 ha		
	Percent of site area in biofilters	Number of biofilters in site	Total biofilter surface area (ha)	Percent of site area in biofilters	Number of biofilters in site	Total biofilter surface area (ha)
Large biofilters, each 435 ft^2 (40.4 m^2)	5	922	3.7	5	999	4.0
	7.5	1377	5.6	7.5	1501	6.1
	10	1838	7.4	10	1998	8.1
Small biofilters, each 200 ft^2 (18.6 m^2)	5	2004	3.7	5	2176	4.0
	7.5	2997	5.6	7.5	3260	6.1
	10	3997	7.4	10	4330	8.1

Table 3
Expected baseline total phosphorus (TP) loading from runoff for the institutional and industrial sites and their drainages, as modeled with SLAMM. Annual averages based on precipitation data from the years 2000 through 2006 from a nearby airport. 1 ha = 2.47 acre; 1 kg = 2.2 pounds (lbs).

Institutional site (Allston) drainage areas	Area of drainage (ha)	TP-loading from runoff (kg P) from 2000-2006	Annual P-loading per ha (kg)
Drainage A	13.15	315	3.4
Drainage B	24.13	813	4.8
Drainage C	11.72	379	4.6
Drainage D	7.13	132	2.6
Drainage E	18.49	304	2.3
Site total	74.62	1943	
Annual average TP loading		277.6	

Industrial site (Zakim) drainage areas	Area of drainage (ha)	TP-loading from runoff (kg P) from 2000–2006	Annual P-loading per acre (kg)
Drainage W	8.24	201	3.5
Drainage X	14.04	197	2.0
Drainage Y	34.12	506	2.1
Drainage Z	24.58	1046	6.1
Site total	80.98	1950	
Annual average TP loading		278.6	

industrial sites (Table 4). Thus for the 5% total pond area model, a single 3.74-ha (9.25 acre) pond at the institutional site achieved the 65% P-removal target, as did one 4.05-ha (10 acre) pond at the industrial site. The more rigorous 75% P-removal target was achieved with a pond covering 15% of either site.

3.3. Scenarios 1–5 with 10–15% pond surface area

The other five detention pond policy scenarios were compared in model runs using ponds covering 10% or 15% of the area drained to them. Scenarios 1–5 represent a gradient of increasing numbers and decreasing sizes of treatment ponds. Scenario 1 treats runoff with one pond per drainage (see Section 2.5, and Figs. 2 and 3). Scenario 2 uses one pond for each source ≥1.62 ha (4 acre), Scenario 3 uses one pond for each source ≥0.81 ha (2 acre), and Scenario 4 uses one pond for each source ≥0.4 ha (1 acre). Scenario 5 equals Scenario 4 except that one additional pond is used at the outfall of each drainage to receive runoff from sources ≤0.4 ha (1 acre) in size.

Only Scenarios 1 and 5 achieved the 65% P-reduction target for both the institutional (Allston) and industrial (Zakim) sites (Figs. 7 and 8). Also, variability in P-removal from drainage to drainage was lowest in Scenarios 1 and 5. Even when modeling ponds at 15% of the areas draining to them, Scenarios 2, 3, and 4 do not achieve the 65% P-removal treatment criterion. Little gain in P-removal occurs when increasing total pond area from 10% to 15% of a site.

P-removal results varied across individual drainages for both sites (Figs. 7 and 8), with greater variation among the drainages at the industrial site (Zakim). Only the individual drainages B and Z (Figs. 2 and 3) achieved the 65% P-reduction level under Scenarios 3 and 4. However, with Scenarios 1 and 5 almost all individual drainages attained the P-reduction target. Thus, the most effective scenarios were treating all site runoff using one pond per drainage (Scenario 1) and using many small ponds to treat all runoff in all drainages of a site (Scenario 5).

Table 4
One Pond Scenario results for total phosphorus (TP) removal. In a model run, a single pond is located at the outfall to collect all stormwater runoff from the site (See Section 2 for calculation of phosphorus removal).

Pond area (as percent of a total site)	5%	7.5%	10%	15%
Institutional site (Allston) % TP-removal	67.9	71.9	74.2	76.8
Industrial site (Zakim) % TP-removal	67.5	72.0	74.3	77.2

Except for the General Industrial site “Z” in Zakim, the attainment of 75% P-removals only occurred with Scenarios 1 or 5 (Figs. 7 and 8). The P-removal results from scenario to scenario varied more widely than did changing the size of an individual pond or changing total pond area within a drainage. Thus, the results for individual drainages suggest that placement of ponds within the study sites—with pond locations and drainage systems planned to maximize the land area from which runoff is treated—is more important than the size of the individual ponds and more important than total pond area.

3.4. Scenario 1 with 5–15% pond surface area

After evaluating the 10% and 15% pond coverage results, we modeled Scenario 1 with ponds at 5% and 7.5% of the areas draining to them to see if the P-reduction target could be achieved with less land area devoted to stormwater treatment. For all pond coverages of a site, 5% to 15%, the institutional site has a higher average P-removal level with less variability among drainages than the industrial site.

For the institutional site, all but one drainage (D) (see Fig. 2) met the 65% target with ponds designed to cover only 5% of the drainage area (Fig. 9). In contrast, for the industrial site, only one drainage (Z) (see Fig. 3) met the P-removal target at 5% pond coverage, and only one other drainage (W) met the target at 7.5% pond sizing (Fig. 9). These results indicate drainage-specific variation in the need for larger or smaller treatment ponds. At 5% pond coverage, none of the drainages in either study site achieved 75% P-removal. However, Drainage E (institutional site) and Drainage Z (industrial site) both exceeded the safety-margin of 75% P-removal using 7.5% pond coverage.

3.5. Summary of detention pond modeling results

While employing any of the six policy scenarios explored in these detention pond modeling trials will help reduce P-loading to the Charles River from the Allston and Zakim sites, only certain scenarios successfully reached the Phosphorus TMDL target of a 65% reduction from commercial, institutional, and industrial sites in the lower river basin. The One Pond Scenario (one pond at the site outfall) consistently met the 65% goal, even with 5% pond coverage. Scenarios 1 and 5, which achieved averages across all drainages of 70–80% P-reduction with 10% and 15% pond coverages, greatly out-performed Scenarios 2, 3, and 4 at both sites. The most likely reason is that in addition to the One Pond Scenario, only Scenarios 1 and 5 require all runoff from the entire site's drainage area to be directed to a pond. When Scenario 1 (one pond for each drainage) was evaluated using the smaller pond sizings of 5% or 7.5%, SLAMM modeling still showed promising average P-reductions of 62–79% for the sites, as well as 50–80% P-reductions in individual drainages.

3.6. Biofiltration scenarios with 5–10% total biofilter surface area

Modeling for different biofiltration scenarios used large and small biofilters (Table 2) and biofilters designed with and without underdrains. Based on the lesson from detention pond modeling trials, that runoff from 100% of a site needed to be directed to a pond in order to achieve the 65% goal, all the biofiltration modeling trials applied biofilters across the entire study site. That is, no biofiltration trials applied biofilters to a subset of sources; rather, runoff from all sources was directed to biofilters in every modeling trial.

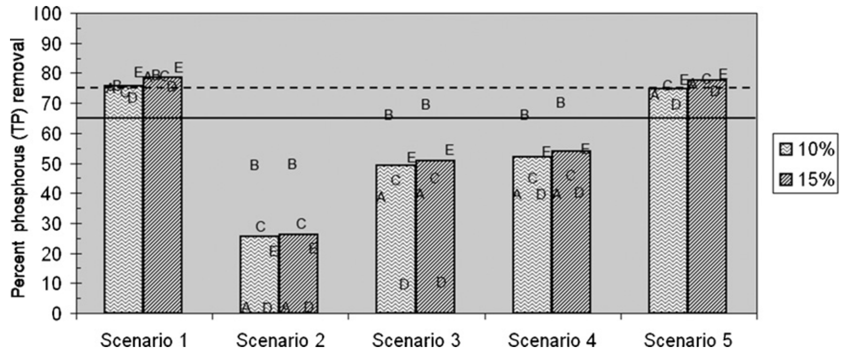

Fig. 7. Institutional site (Allston): phosphorus removals for modeled Scenarios 1–5 with ponds occupying 10% and 15% of the area contributing runoff. Scenarios 1–5 represent a gradient of increasing numbers and decreasing sizes of treatment ponds (see Table 1). Histograms indicate the average phosphorus reductions from all five drainages weighted according to the area of a drainage. The solid horizontal line highlights the regulatory 65% P-reduction goal; the dashed line indicates a safety margin of 75% P-reduction. Letters A–E represent the percent reduction in TP for individual drainages (see Fig. 2). [Note that, due to SLAMM complications, the result for Scenario 5 Drainage B was incalculable and is not included in the weighted average. However, Scenario 4 for Drainage B did achieve the 65% reduction, so it can be assumed that Scenario 5, which adds an additional pond, would achieve the TMDL as well.]

A "Land Use Biofiltration" function in WinSLAMM simplified the biofilter modeling process compared with detention pond modeling (see Section 2.2). Each modeling trial was evaluated for the entire study site, and reflects the cumulative phosphorus-removal (TP) from the site's constituent land uses. Accordingly, fewer modeling trials were conducted for biofiltration. All biofilters in each trial were identical replicas of each other and >4000 biofilters could be evaluated in one model run. The variables in the biofiltration

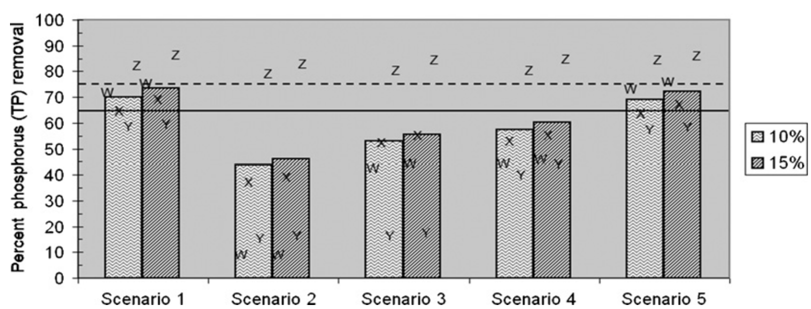

Fig. 8. Industrial site (Zakim): phosphorus removals for modeled Scenarios 1–5 with ponds occupying 10% and 15% of the area. Histograms indicate the average phosphorus reductions from all four drainages weighted according to the area of the drainage. Letters W–Z represent the percent reduction in TP for individual drainages (see Fig. 3). See Fig. 7 caption.

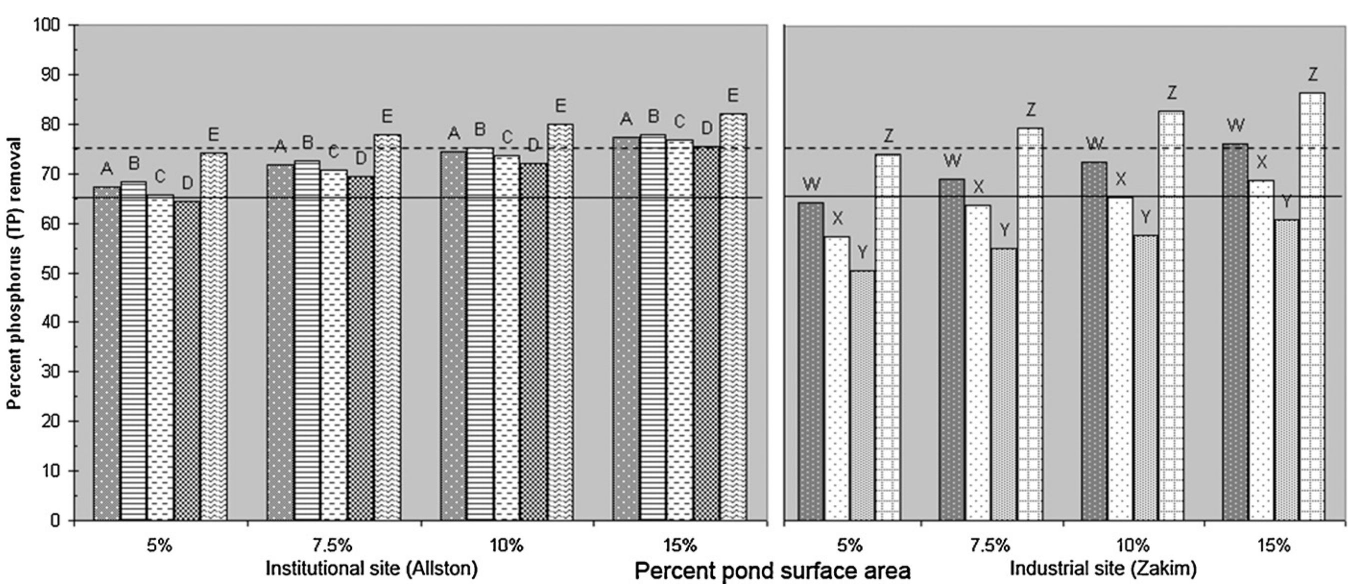

Fig. 9. Phosphorus reductions modeled for Scenario 1—one pond per drainage—with ponds covering 5–15% of their drainages. Institutional site weighted averages ranged from 68.8% P-removal (with a 5% pond) to 78.5% P-removal (with a 15% pond). Industrial site weighted averages ranged from 61.9% to 73.4% P-removal. Letters refer to specific drainages in a site (Figs. 2 and 3).

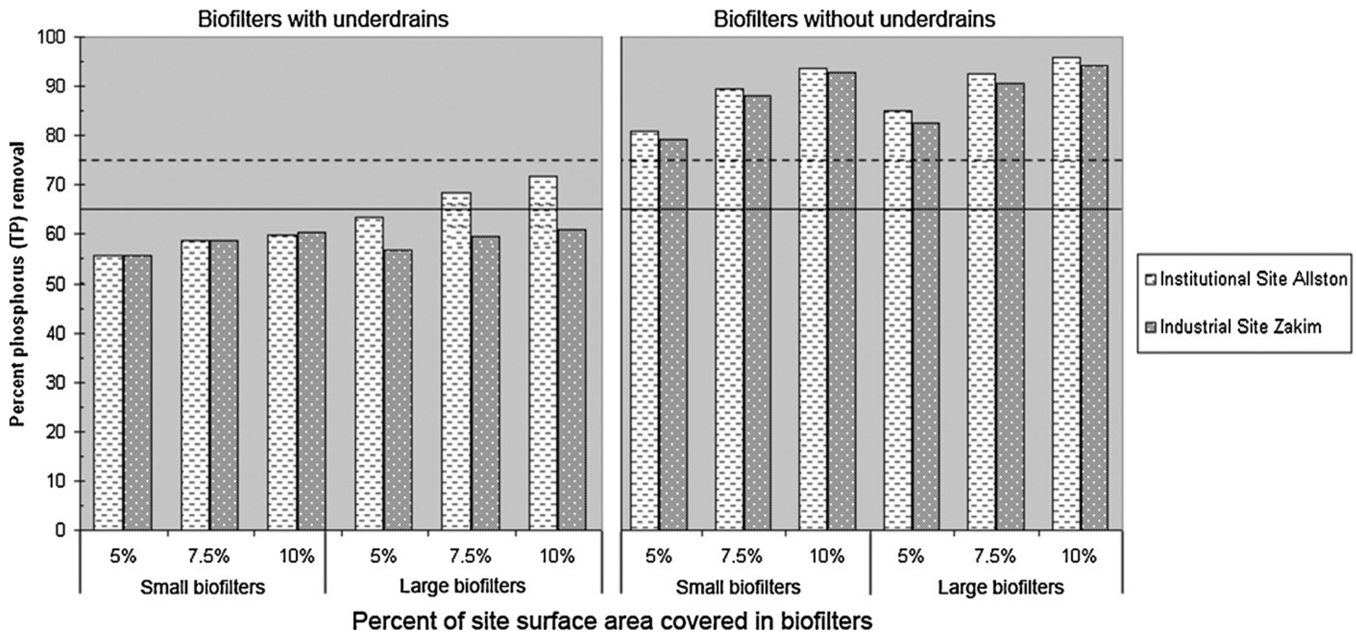

Fig. 10. Phosphorus removal by numerous biofilters modeled for the institutional and industrial sites. Small = 18.6 m^2 (200 ft); large = 40.4 m^2 (435 ft^2). Number of biofilters ranges from 922 to 4330 per site (see Table 3).

scenarios are the percent of the drainage occupied (5–10%) and the size of the biofilter—large 40.4 m^2 (435 ft^2) and small 18.6 m^2 (200 ft^2)—(Table 2), as well as the presence or absence of an underdrain at the bottom of each biofilter. The number of biofilters allocated to each land use within a site was proportional to the area of that land use.

Removal of phosphorus with biofiltration is much more effective without underdrains (Fig. 10). All of the trials with no underdrains exceeded the 65% P-removal goal, at both sites with only 5% coverage by biofilters. Impressive P-removals ranged from 79% to 95%. For biofiltration with underdrains, only two trials, both in the institutional site and using large biofilters, achieved the 65% goal. However, all biofilter scenarios that included underdrains exceeded 55% P-removal (range of 55–71%).

Despite occupying the same surface area on land as the small biofilter scenarios, the scenarios with (fewer) large biofilters often achieved somewhat more P-removal (Fig. 10). In short, for biofiltration, having no underdrains is much more effective than having underdrains present and large biofilters are slightly better than small ones for stormwater phosphorus removal.

3.7. Summary of modeling results: most promising pond and biofilter scenarios

For both the institutional and industrial sites, the water quality target was met by a single pond (at the outfall of a site) covering only 5%, or more, of a site (Fig. 11). Also, small or large biofilters (without underdrains) with 5% total coverage achieved the 65% P-reduction level. Several multi-pond or biofilter arrangements covering 10% of a site reduced phosphorus by 65%. The more stringent clean-water goal of 75% P-removal was met only by biofilters (without underdrains) at 5% (or more) coverage of a site, as well as by certain pond arrangements with 15% cover (Fig. 11).

Overall, P-removal levels were quite similar for industrial and institutional land uses (Fig. 11). With 10% pond coverage across either site, the 65% P-removal target was only met when runoff from the entire site entered detention ponds. This is exemplified by comparing Scenarios 4 and 5, wherein the additional pond in Scenario 5 accepts otherwise untreated water and achieves the 65% goal that is unattainable by Scenario 4 (Figs. 7 and 8). Approximately the same P-reduction levels were achieved using few (4–5) large ponds (consolidated arrangements) or many (29–40) smaller ponds (dispersed arrangements). Modeling indicated that the configuration of stormwater treatment landscapes is apparently a more important variable than total treatment area. All of the most promising scenarios required ponds or biofilters that accepted runoff from 100% of the land area generating stormwater within a site. In short, several stormwater treatment design options are available to meet the 65% phosphorus-reduction target, and a few designs achieve the enhanced clean water goal of 75% phosphorus-reduction for large urban sites.

4. Discussion

We found that the only treatment designs that achieved the 65% P-reduction target were those for which stormwater from 100% of the urban land flowed into detention ponds or biofilters. If this criterion was met, then pond/biofilter coverage could be as low as 5% and successfully meet the TMDL goal for the Charles River of 65% P-removal.

According to the SLAMM modeling results, if one single pond is designed to collect the drainage from 75 ha (~185 acre) or 80 ha (~200 acre), the pond must cover at least 5% of the site's area to meet the 65% goal (Table 4). Considering that 67% P-removal was the lowest One Pond result with 5% pond sizing, it is not likely that ponds sized <5% of the land area would achieve the 65% target.

Scenarios 1 and 5 are both successful because they operate on the same principle: every drop of stormwater runoff from the whole study site is routed through a pond. This concurs with a watershed management approach (Tilley and Brown, 1998), which suggests that stormwater runoff "management alternatives need to be developed for the entire watershed rather than only for a subset of areas" (Jing et al., 2006).

Not all policy scenarios for detention ponds or biofiltration would meet the phosphorus reduction goal if implemented to address stormwater treatment at the two sites. However, certain consolidated options and dispersed options would meet the

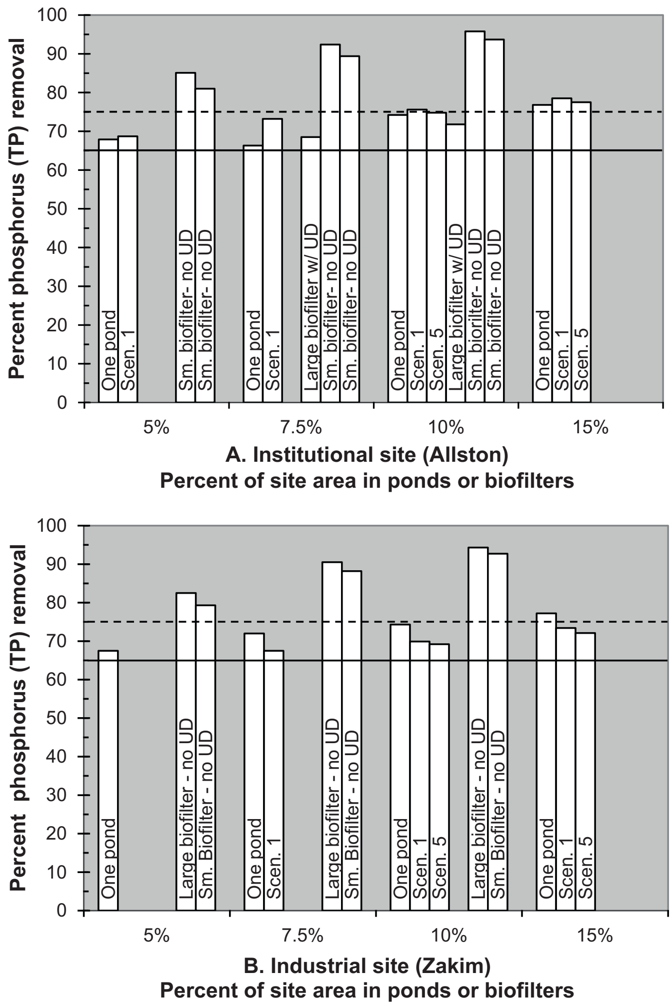

Fig. 11. The most promising scenarios, achieving 65% or more phosphorus removal for (A) institutional site and (B) industrial site. UD = underdrain. For detention pond Scenarios 1 and 5, percent P-removal is a weighted average of reductions in P modeled for each drainage in a site (5 drainages in institutional Allston and 4 drainages in industrial Zakim). Scenario 5 for 5% and 7.5% pond sizes and biofilters at 15% were not studied. The number of stormwater treatments varied from one ("One pond") to >4000 ("Small biofilters" with 10% coverage per site).

P-removal goal. For both sites, the One Pond Scenario used a single pond with as low as 5% site coverage to achieve the TMDL (Table 4). From a design and planning standpoint, it is interesting to note that, for both study sites, Scenario 1 and 5 achieved very similar weighted average P-removals across all drainage areas (Figs. 7 and 8) by employing distinctly different policies, i.e. a single pond in each drainage *or* many smaller ponds (with the same total area) in a drainage. SLAMM modeling for both the institutional and industrial study sites showed that single detention ponds *and* multiple detention ponds could both successfully meet the TMDL.

Meanwhile, the interpretation of the pond modeling results depends upon whether one is looking at the drainages of a study site independently or considering it collectively with other drainages on site. For the individual drainages in the institutional site (Allston), Scenario 1 and Scenario 5 both met the 65% goal in model trials, with ponds occupying 10% and 15% of all five drainage areas (A, B, C, D, and E). By contrast, not all drainages in the industrial site (Zakim) met the 65% target when applying Scenarios 1 and 5. Neither scenario achieved the 65% goal for Drainage Y, even with 15% pond coverage. Yet the other drainages (W and Z) had comparatively high % P-removals. Therefore, when considering all the drainages in a site together, with weighted averages (based on the four drainages' respective land areas), the 65% goal was achieved using both Scenarios 1 and 5 at 10% pond coverage. While we did not evaluate Scenario 5 for 5% or 7.5% pond coverages, it is possible that even smaller detention ponds could also allow Scenario 5 to meet the TMDL, assuming the drainages' respective P-removals were averaged together.

In terms of recommending policy scenarios (e.g., those in Tables 1 and 2), these SLAMM modeling results suggest that all runoff from all land areas needs to be treated in order to reach the 65% reduction target. Scenario 3, with pond treatment of sources ≥2 acres (0.81 ha), is the most similar to the U.S. Environmental Protection Agency's current proposed policy for its pilot study of stormwater regulations in the Charles River watershed (EPA, 2008). This policy scenario does not prove adequate for meeting the TMDL goal for the two sites evaluated. Further, even with Scenario 4, which calls for sites of ≥1 acre (0.4 ha) to be retrofitted, the 65% goal was not achieved for either study site (Figs. 7 and 8). The many sources in the two study sites (i.e., impervious surfaces that are smaller than one acre, which are abundant in most all cities) collectively generate so much stormwater and phosphorus pollution that leaving them untreated prevents the TMDL goal from being achieved.

As previously described, no area was left untreated in the biofilter scenarios. For both sites, runoff from all land area was modeled to be directed to a biofilter. Large biofilter scenarios outperformed scenarios with small biofilters (Fig. 10). Larger biofilters have the capacity to attenuate greater volumes of runoff in the subsurface portions of the biofiltration cells. This is because the upper section of the biofilters slope toward the subsurface soil and rock layers making the underground footprints of biofilters smaller than their areal coverages (Fig. 6); the smaller biofilters have proportionately less storage space.

Because the biofilters without underdrains relied almost exclusively on infiltration and the modeled biofilters were designed to have the lowest possible infiltration rates (see Section 2.3), stormwater had a longer residence time in model trials excluding underdrains, and phosphorus removal was the highest reported. It is also possible that the presence of underdrains in the model trials facilitated the export of dissolved phosphorus from biofilters, decreasing treatment for this form of the total phosphorus (TP); i.e., only the particulate forms of P were treated according to the model when an underdrain was present.

These results might suggest that underdrains simply not be used. Dietz and Clausen (2008) questioned whether biofilter underdrains were appropriate in all settings. Davis et al. (2009) report a lack of consensus about underdrains' effects on water quality. However, underdrains are generally recommended for urban biofiltration (Massachusetts, 2008; University of New Hampshire Stormwater Center, 2010) to minimize long-term ponding, to reduce potential contamination of runoff by soils adjacent to the biofilter and as a convenient subsurface connection for biofilter overflows into existing storm sewer systems. Underdrains are also useful in cases where water collected in biofilters is to be re-used on site, such as in landscape irrigation or toilet flushing in buildings. It is quite possible that with some tweaking of the biofilter designs that were used for modeling purposes (for example, adding volume capacity by increasing depth, or changing the soil mix), the biofiltration scenarios with underdrains would prove adequate for meeting the TMDL, even for the highly impervious case study sites.

The One Pond Scenario consistently used less land area to achieve the P-removal goal of 65% than any other pond scenario for both sites (including Scenario 1 with 5% and 7.5% pond sizing). The major challenges of implementing the One Pond Scenarios are finding the space in urban settings to design a functional stormwater pond system at the scale of 4 ha (10 acres) and ensuring that it is properly maintained, as all the stormwater treatment to meet the TMDL would be dependent on a single system. On the other hand, maintenance would also be a challenge in designs that disperse stormwater runoff into thousands of biofilters, e.g., as in the promising set of scenarios for biofilters without underdrains, which also achieved the TMDL goal using 5% of urban land area.

Altogether, we used WinSLAMM to model baseline P-loading conditions for each site, plus 140 different drainage scale and site scale modeling trials (116 pond trials and 24 biofilter trials). The percents of P reduction achieved through modeling for both sites using SLAMM are comparable to those found in the literature (e.g., Davis et al., 1998; Pitt and Voorhees, 2003a; Weiss et al., 2007). We believe the results indicate that it is possible to meet the Charles River Phosphorus TMDL by implementing policies that are adequate to require landscape retrofits of urban sites, whether by consolidated or dispersed stormwater treatment. Designers and planners can create stormwater treatment landscapes that facilitate sedimentation, adsorption to particles, and biological uptake of phosphorus; these landscapes can be used to achieve the TMDL.

All modeled scenarios for both detention ponds and biofiltration significantly improved water quality, as measured by phosphorus pollution to the Charles River, compared with existing conditions. At least half of the P-loading was curbed in all scenarios modeled. In general, P-removal results for detention ponds were better when considering the average from all drainages in a site than when drainages were evaluated individually. This 'combining and averaging' points to a policy solution: runoff from the individual drainages or sources for which the policy scenarios cannot achieve the P-removal goal could be combined with runoff from other adjacent areas—with less pollution or more pervious area—for which the policy scenarios surpass the 65% goal. This would enable both neighboring sites to meet the 65% P-removal goal collectively before discharging runoff into the storm drainage system or the outfall to the Charles River.

If it is practical to combine runoff from multiple source areas before it flows into the storm drainage system, this collaborative treatment approach may benefit multiple parties in terms of finding sufficient land area as well as design and construction costs. Where ponds are deemed the best solution, policy makers should encourage (and avoid prohibiting) the agglomeration of runoff from multiple sites for the purpose of stormwater management. For biofilters, a similar approach of sharing resources could be used for designing, constructing, and maintaining multiple biofilters across different properties, even as biofiltration necessitates a more dispersed stormwater plan. To facilitate this type of collaborative thinking, urban parcels could be organized in watershed-based (or drainage-based) districts, acknowledging existing storm drainage pipe networks and maximizing the performance and success of stormwater treatment landscapes.

The hypothetical policy scenarios chosen for ponds, ranging from "consolidated" to "dispersed" pond arrangements across an urban site, as well as "highly dispersed" biofilters across a site, were intended to present a spectrum of possible stormwater treatment designs that could be modeled and compared. Applying any of these scenarios to real sites would make stormwater treatment highly visible across an urban area. While visibility of infrastructure (and the natural processes infrastructure sometimes mimics) is often desirable (e.g., Brown et al., 1998; Hill, 2003; Hurley, 2009), there are ways to reduce the footprints required for stormwater treatment. For example, reducing impervious surfaces, or adding green roofs, infiltration trenches, or porous pavements, will help lessen the required areas for stormwater treatment. In choosing the best array of stormwater treatment landscapes, other factors such as the comparative cost of various solutions, integration with transportation infrastructure, community needs for open space and greenspace, aesthetics and habitat values can help determine the best arrangements of these stormwater landscapes on a site by site, or watershed by watershed, basis. Knowing that the SLAMM modeling process revealed successes across the scenario spectrum should give planners freedom to explore new stormwater landscape solutions.

5. Conclusions

This research shows that the goals of the Charles River Phosphorus TMDL can be achieved with realistic allocations of area for stormwater treatment. We found that stormwater treatment can be accomplished with many tiny insertions arranged in the urban fabric, or in one grand planning gesture (or perhaps a hybrid of these two arrangements). Future research should investigate innovative regulatory policy scenarios that require improved water quality through stormwater treatment, while allowing industrial, commercial, and other urban property owners to have some flexibility in the ways in which they choose to reduce pollution from their sites. Such solutions should also provide numerous opportunities for community, neighborhood, drainage, and watershed-based partnerships to achieve pollution reduction goals and clean urban rivers.

Acknowledgments

The authors wish to thank Christian Werthmann (Harvard University), Tim Baird (Pennsylvania State University) and Mark Brenner (University of Florida) for reviewing sections of this manuscript. We thank Viola Augustin for assisting with the detention pond section figure. Comments from two anonymous reviewers improved this manuscript. We also thank Mark Voorhees (U.S. Environmental Protection Agency), Kate Bowditch (Charles River Watershed Association), Christopher Kilian and Cynthia Liebman (Conservation Law Foundation), John Voorhees (PV & Associates), and Breck Bowden (University of Vermont) for their support and valuable feedback.

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